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MINIMUM VENTILATION REQUIREMENTS FOR WIND-PRESSURE-EXPOSED ENVIRONMENTAL ENCLOSURES

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Field operations that require secondary containment structures are often exposed to wind. The airflow patterns around a structure can affect the structure containment level and personnel safety. The wind pressure is calculated to determine the maximum wind speed at which the structure can provide adequate containment. Recommended structural components are described, including testing requirements for verifying adequate containment. The procedure for converting air velocity measurements into actual values is explained.

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PREFACE

The work described in this report was started in February 2017 and completed in June 2018.

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1. INTRODUCTION

1.1 Background

Many operations in the field require a secondary containment system, to prevent the release of contaminants into the atmosphere in the event of an accidental chemical leak or spill. An example is the Explosive Destruction System (EDS), which requires an environmental enclosure structure to provide containment and appropriate indoor environmental conditions during the EDS operations. Containment of any chemical agent that may escape the EDS is a critical function of the enclosure.

These types of structures are often located outdoors, where they are exposed to constantly changing weather conditions. They are typically constructed of an aluminum support frame covered with a flexible material such as polyester.

Operations within the environmental enclosure require a specific indoor temperature as well as 100% exhaust air, to prevent propagation of contamination within the structure. The heating, ventilation, and air conditioning (HVAC) system and the exhaust filtration system should be properly balanced to provide the required negative pressure within the structure.

These types of structures have some limitations, such as structural capacity and air-leak tightness, but the most important factor affecting the ability of the structure to provide proper containment is the wind pressure (Figure 1). To prevent loss of containment, the wind speed should be measured so that the pressurization effect over the structure can be determined. This exterior pressure should not exceed the internal negative pressure within the structure.

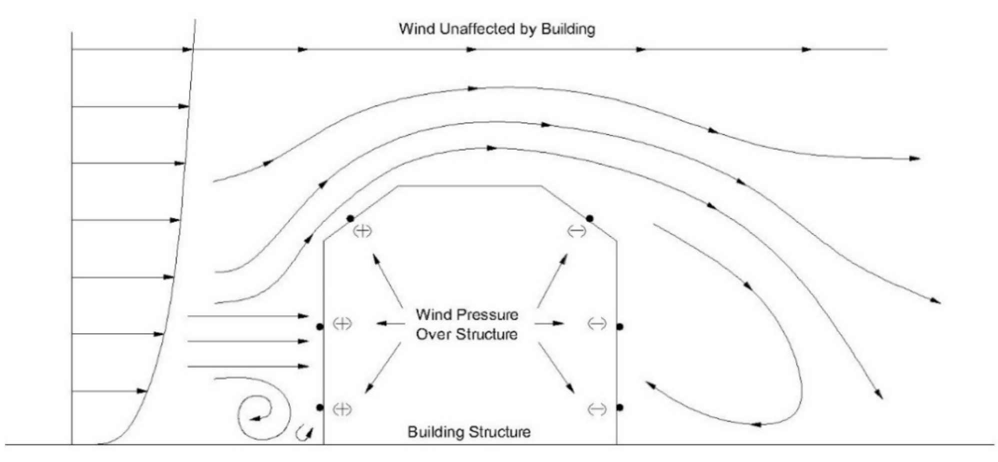

Figure 1. Wind pressure around environmental enclosures.

This report describes the basic ventilation requirements for these types of environmental enclosures during exposure to windy conditions.

1.2 Description

The environmental enclosure ventilation system (Figure 2) is composed of a main structure, an ingress/egress system, a conditioned air-supply system, and an exhaust filtration system.

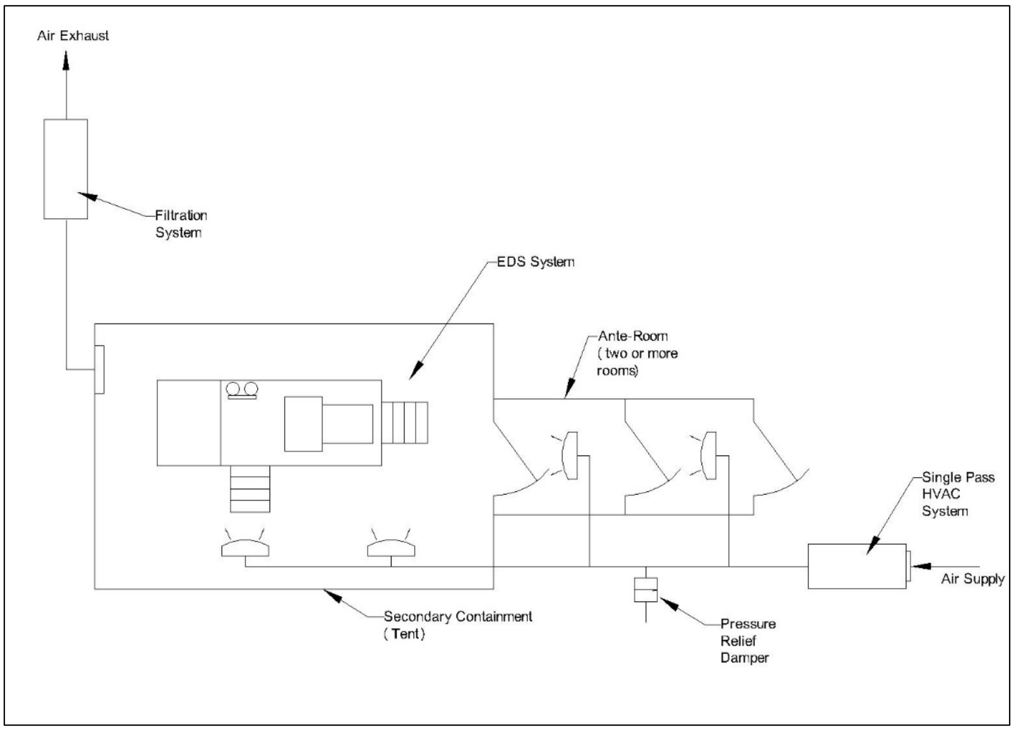

Figure 2. Concept figure diagram of the environmental enclosure system.

The *main structure* provides containment during field operations to prevent the release of contaminants to the atmosphere. It also provides adequate indoor environmental conditions for safe operations. The actual indoor environmental conditions are established in the destruction plan or standing operating procedure for each field operation. The structures are typically constructed with flexible wall materials.

The *ingress/egress system* is a cascading air system that is designed to prevent airflow from the most potentially contaminated area into less-contaminated areas. At a minimum, the ingress system consists of a vestibule area that is immediately adjacent to the main enclosure. The egress system for personnel leaving a potentially contaminated area requires several stages. Each area must maintain the directional flow, as previously indicated. The first stage connected to the outside is considered to be a clean area. Conditioned air is supplied to this area, and properly designed air diffusers must be provided to avoid air turbulence.

The *air-supply system* provides conditioned air to the ingress/egress area as well as the main enclosure. This system does not recirculate air from the environmental enclosure. The air-supply diffusers should be properly specified to prevent turbulence, especially in the ingress/egress area. The air supply does not require temperature or humidity conditioning if the outside air temperature and humidity meet the required environmental conditions for field operations.

The *exhaust filtration system* consists of at least one high-efficiency particulate air (HEPA) filter bank (on the upstream side) and two high-efficiency gas adsorber (HEGA) filter banks. Each HEGA filter bank should provide a minimum of 0.25 s of residence time. The HEGA filter bank should be of sufficient size to capture the chemicals released from the most credible event using the first bank of filters, and the second bank should be maintained for system redundancy. The filtration system must be equipped with all required ports for HEPA and HEGA filter testing, and differential pressure gauges will be installed on all filter banks.

2. CONTAINMENT CONTROL

The environmental enclosure should maintain containment of any contaminant released within the structure, at all times. The negative pressure value in the enclosure plays an important role in maintaining the required containment level.

In the event of an exhaust system failure, the supply system will be interlocked to initiate the shutdown of the air-supply unit. This action will prevent positive pressurization within the structure. Additionally, in the event of an air-supply system failure, a pressure-relief damper should provide release of negative pressure, to maintain a safe level of negative pressure in the structure (Figure 2).

Before operations are initiated, the environmental enclosure ventilation system should be tested and certified in accordance with the U.S. Army Edgewood Chemical Biological Center’s Chemical Surety Ventilation Program.[1] Airflow measurements obtained with thermal anemometers or Pitot tubes may need corrections to indicate actual velocity values at the local air density. If local temperature and humidity levels are relatively high, an additional correction factor may be required to obtain the actual velocity of moist air. Refer to the appendix for more information.

The pressure monitoring system measures the static differential pressure of the environmental enclosure in reference to the outdoor barometric pressure. The system consists of a differential pressure gauge with visual and sound alarms, a manifold system with a minimum of four pressure measuring ports, and an outdoor static pressure sensor. This system should provide an accurate measurement of the enclosure static pressure in reference to the outside area without interference from wind pressure.

To allow for verification of the pressure gauge readings during certification of the ventilation system, the system should include testing ports. Only calibrated instruments should be used for verification tasks.

Typical equipment used in this setup includes the following:

- a Digihelic gauge (model DH-006; Dwyer Instruments; Michigan City, IN);
- a static pressure head (model SPH20; Vaisala Corporation; Helsinki, Finland); and
- a wind monitoring station (model WMS-20; Omega Engineering; Norwalk, CT).

Figure 3 indicates how these instruments will be used within the structure.

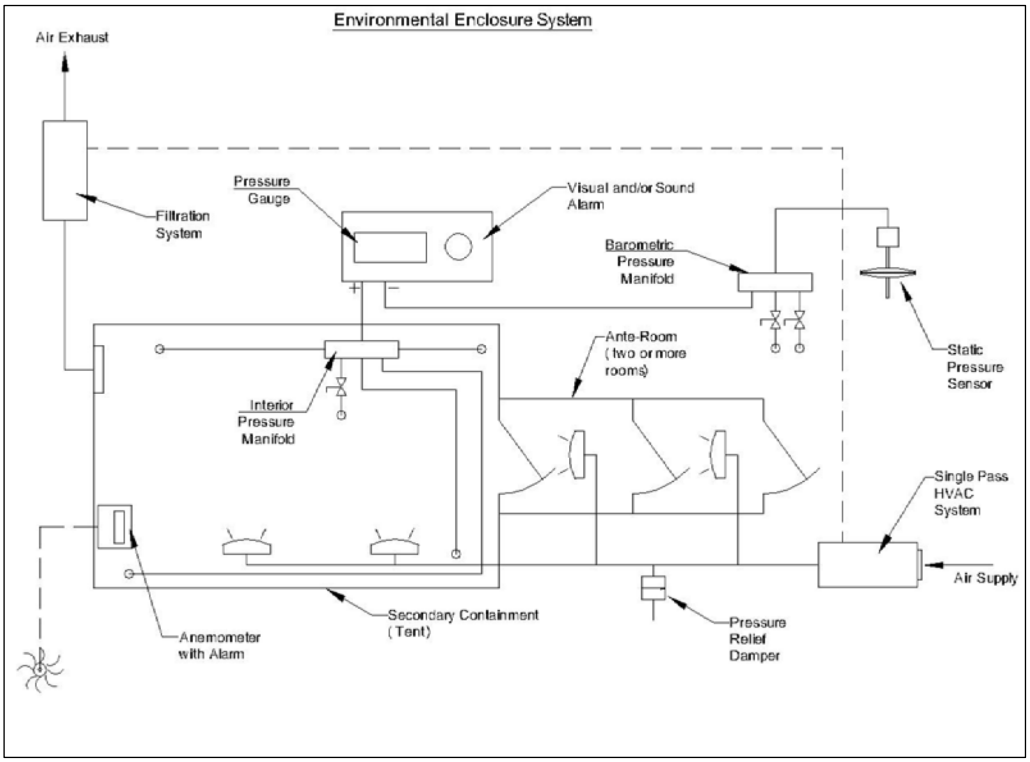

Figure 3. Concept diagram of the EDS pressure monitoring system.

3. WIND PRESSURE CALCULATION

Local wind pressure around a low-rise building depends mainly on the building shape and the wind direction. Some building sections will be exposed to positive and negative pressures. Negative-pressure areas can cause loss of containment within a building's internal area.

The following formula can be used to estimate local pressure values:[2]

$$P_w = K\rho_a C_p \frac{U_h^2}{2} \tag{1}$$

where

P_w is the wind velocity pressure, in inches of water gauge (in.-wg);
K is the unit conversion factor, 0.01284166;
ρ_a is the local air density (in lb/ft^3), which is 0.075 at 70 °F and 29.92 in.-Hg barometric pressure;
U_h is the approach wind speed at upwind wall height (mph); and
C_p is the local pressure coefficient (values obtained from the 2017 *ASHRAE Handbook*[2]).

When using hourly wind-speed information from a nearby meteorological station, the local wind speed U_h is estimated by applying terrain and height corrections as follows:[2]

$$U_h = U_{\text{met}} \left(\frac{\delta_{\text{met}}}{H_{\text{met}}}\right)^{a_{\text{met}}} \left(\frac{H}{\delta}\right)^{a} \quad (2)$$

where
U_{met} is the hourly wind speed from the meteorological station (mph);
δ_{met} is the atmospheric boundary layer thickness at the meteorological station (ft);
H_{met} is the height of the recorded wind speed (ft);
a_{met} is the exponent for the local building terrain at the meteorological station;
H is the structure height (ft);
δ is the atmospheric boundary layer thickness at the structure location (ft); and
a is the exponent for the local building terrain at the structure site.

The values for the exponents a and δ can be found in the 2017 *ASHRAE Handbook*, Chapter 24, "Airflow Around Buildings", Table 1.[2]

For most meteorological stations, typical values for a and δ are 0.4 and 900 ft, respectively. These values are for areas of open terrain with scattered obstructions that have heights of less than 30 ft, including flat, open country.

4. EXAMPLES

4.1 Wind Velocity Calculation Example

Calculate U_h, assuming the wind speed U_{met} is obtained from a meteorological station located on open terrain with scattered obstructions. This velocity is typically obtained at 33 ft from the ground level (H_{met}).

The height of the environmental enclosure is 14 ft, 8 in. It is located in a suburban area that includes numerous closely spaced obstructions that are the size of single-family dwellings. Use eq 2, with the following values: U_{met} is 25 mph; δ_{met} is 900 ft; H_{met} is 33 ft; a_{met} is 0.14; H is 14 ft, 8 in.; δ is 1200 ft, suburban area; and a is 0.22, suburban area.

Therefore,

$$U_h = 25\left(\frac{900}{33}\right)^{0.14} \left(\frac{14.67}{1200}\right)^{0.22} = 15.1 \text{ mph} \quad (3)$$

4.2 Wind Pressure Calculation Examples

Using eq 1 for different wind speeds, the value of the wind pressure at the edge of the roof is greater for roof slopes of less than 15°. The maximum value is found at a 10° slope, which results in a C_p of –1.8,

5 mph: $P_w = 0.01284166 \times 0.075 \times (-1.8) \times \frac{5^2}{2} = -0.022$ in.-wg

10 mph: $P_w = 0.01284166 \times 0.075 \times (-1.8) \times \frac{10^2}{2} = -0.087$ in.-wg

20 mph: $P_w = 0.01284166 \times 0.075 \times (-1.8) \times \frac{20^2}{2} = -0.347$ in.-wg

For roof slopes of 15° or greater, the C_p value decreases to a maximum of –0.9,

5 mph: $P_w = 0.01284166 \times 0.075 \times (-0.9) \times \frac{5^2}{2} = -0.011$ in.-wg

10 mph: $P_w = 0.01284166 \times 0.075 \times (-0.9) \times \frac{10^2}{2} = -0.043$ in.-wg

20 mph: $P_w = 0.01284166 \times 0.075 \times (-0.9) \times \frac{20^2}{2} = -0.173$ in.-wg

A more precise value for wind pressure can be obtained by calculating the structure's roof slope from the actual dimensions and using the values from Table 1 to obtain the C_p value.

Table 1. Values for Calculating Wind Pressure

Roof slope	0°	3°	10°	15°	20°	30°
Maximum C_p	–1.6	–1.3	–1.8	–0.9	–0.6	–0.7

Note: Values in Table 1 were obtained from the 2017 *ASHRAE Handbook*,[2] Chapter 24, "Airflow Around Buildings", Figure 8. The negative sign indicates negative pressure over the structure.

5. EXPLOSIVE DESTRUCTION SYSTEM ENCLOSURE DIFFERENTIAL PRESSURE

Several factors can affect the differential pressure within the enclosure, such as the following:

- the structural integrity of the enclosure,
- the air leakage within the structure,
- the supply airflow, and
- the exhaust airflow.

Once the enclosure is installed and the ventilation system is functioning, a complete test is required. In this test, the following tasks are performed:

- filtration system leak test, which is performed at the working airflow condition;
- air-supply system check (if needed), to verify that proper airflow and temperature are being used;

- interlock of supply–exhaust system: in this case, the supply system should turn off in the event of an exhaust system failure;
- relief damper pressure verification: under high negative pressure within the enclosure, the damper should open when the air-supply system has failed;
- verification of appropriate directional airflow at the ingress/egress area: open doors will be tested individually, each door will maintain a minimum average face velocity of 50 ft/min, and a smoke test will be performed to verify directional airflow is maintained; and
- verification (using a calibrated instrument) that the negative pressure within the enclosure is the same as that indicated by the EDS enclosure pressure monitoring system (Section 2). Testing ports should be available on the barometric pressure manifold and the interior pressure manifold.

The negative pressure P within the EDS enclosure, which is obtained after all systems have been verified, should be used to determine the maximum wind velocity at which the enclosure will provide containment. As discussed in Section 4.2, eq 1 can be rearranged to calculate the maximum wind pressure:

$$U_h = \left(\frac{2P}{K\rho_a\, C_p}\right)^{1/2}$$

where
P is the EDS enclosure differential pressure (in.-wg);
K is the unit conversion factor, 0.01284166;
ρ_a is the local air density, 0.075 lb/ft^3 at 70 °F;
U_h is the approach wind speed at the upwind wall height (mph); and
C_p is the local pressure coefficient (values obtained from the 2017 *ASHRAE Handbook*[2]).

As an example, calculate the maximum acceptable wind velocity when the EDS enclosure differential pressure is –0.15 in.-wg and the roof slope is 10°.

Answer: From Table 1, C_p = –1.8. Then,

$$U_h = \left(\frac{2 \times (-0.15)}{0.01284166 \times 0.075 \times (-1.8)}\right)^{1/2} = 13.2 \text{ mph}$$

This result indicates that 13.2 mph is the maximum recommended wind speed for this particular tent, and for wind speeds greater than 13.2 mph, the EDS enclosure may not provide appropriate containment. At the same time, the wind monitoring station should alarm to indicate wind speeds that exceed the maximum recommended speed.

6. CONCLUSIONS

The environmental enclosure structure is exposed to constantly changing weather conditions. Therefore, it is recommended that the environmental enclosure differential pressure and the wind velocity outside the structure at the wall height level be constantly monitored.

During the planning stage, consideration should be given to selecting structures that will reduce the effects of wind pressure. Structures with roof slopes greater than 15° will provide better containment than those with roof slopes of less than 15°.

Additionally, meteorological wind information should be used during the planning stage to calculate the required negative pressure within the structure. If the structure is located in an area with excessive wind speed, alternatives should be considered, such as locating the structure near natural barriers to protect it from high-speed winds, or building a double-wall structure to mitigate the effects of wind speed.

Because the main structure and support systems may differ from site to site, a recommended first step is to determine the system's capability to maintain sustained negative pressures at safe levels. This differential pressure value can then be used to calculate the local maximum acceptable wind speed that will guarantee proper containment. The wind speed should be continuously monitored to ensure that the maximum acceptable wind speed is not exceeded. The anemometer should be equipped with an alarm that alerts to unsafe conditions when its set point has been exceeded.

Deviations from the basic design should be evaluated on a case-by-case basis by safety or ventilation professionals.

LITERATURE CITED

1. *Chemical Surety Ventilation Program (CVSP), Revision 6.0.* U.S. Army Edgewood Chemical Biological Center: Aberdeen Proving Ground, MD, 2013.

2. Airflow Around Buildings. In *ASHRAE Handbook—Fundamentals*; Owen, M.S., Ed.; ASHRAE: Atlanta, GA, 2017; Chapter 24.

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ACRONYMS AND ABBREVIATIONS

δ	atmospheric boundary layer thickness at local structure
δ_{met}	atmospheric boundary layer thickness at meteorological station
ρ	air density
ρ_a	local air density
a	local structure terrain exponent
a_{met}	meteorological station local terrain exponent
C_p	local pressure coefficient
EDS	Explosive Destruction System
H	wall height of the structure
H_{met}	anemometer height at meteorological station
HVAC	heating, ventilation, and air conditioning
HEGA	high-efficiency gas adsorber
HEPA	high-efficiency particulate air
in.-wg	inches of water gauge
K	conversion factor
P_{atm}	atmospheric pressure
P_{w}	wind velocity pressure
T	temperature
U_h	approach wind speed at upwind wall height
U_{met}	hourly wind speed from a nearby meteorological station
V_{ACT}	actual velocity
$V_{\mathrm{ACT\ dry}}$	actual velocity under dry conditions
$V_{\mathrm{ACT\ moist}}$	actual velocity under moist conditions
Vel	air velocity
V_{NOM}	nominal velocity
$V_{\mathrm{NOM\ dry}}$	nominal velocity under dry conditions
V_p	velocity pressure
V_{STD}	standard velocity
$V_{\mathrm{STD\ dry}}$	standard velocity under dry conditions
w_s	humidity ratio

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APPENDIX:

AIR VELOCITY MEASUREMENTS

Air velocity measurements can be affected by local conditions such as temperature, pressure, and humidity, as well as the methods used to obtain the measurements. Air velocity measurements can be obtained by using thermo-anemometers or manometers. There are advantages and disadvantages associated with both types of instruments.

Thermo-anemometers typically indicate velocities with reference to a set of standard conditions such as 70 °F, 29.92 in.-Hg, and 0% relative humidity. In this case, the indicated velocity is proportional to the mass of air that would be moving through the sensor if the temperature and pressure were at standard conditions. The velocity value obtained is called *standard velocity*.

Pitot tubes provide velocity measurements using a manometer that measures the velocity pressure. The air velocity value for dry air is calculated using

$$\mathrm{Vel} = 1096.8\sqrt{\frac{Vp}{\rho}} \tag{A-1}$$

where
Vel is the air velocity (ft/min),
V_p is the velocity pressure (in.-wg), and
ρ is the air density (lb/ft^3).

The air density for dry air can be calculated from

$$\rho = 1.3256P_{\mathrm{atm}}/(459.67 + T) \tag{A-2}$$

where
P_{atm} is the barometric pressure (in.-Hg), and
T is the temperature of air (°F).

If the actual air density is not determined, the result will be indicated using the standard value for air density (0.075 lb/ft^3). In this case, the velocity obtained is called the *nominal velocity*. If the actual density is used, the velocity value obtained is called the *actual* (or *true) velocity*. This is the velocity at which a molecule travels in the airstream.

The velocity reading from a thermo-anemometer can be related to the reading from a Pitot tube by the following:[A-1]

$$V_{\mathrm{STD\ dry}} = V_{\mathrm{NOM\ dry}}\sqrt{}(\rho_{\mathrm{ACT}}/\rho_{\mathrm{STD}}) \tag{A-3}$$

Or

$$V_{\mathrm{STD\ dry}} = 4.207478V_{\mathrm{NOM\ dry}}\sqrt{}(p_{\mathrm{atm}}/(459.67 + T) \tag{A-4}$$

And

$$V_{\text{ACT dry}} = V_{\text{NOM dry}}\sqrt{}(\rho_{\text{STD}}/\rho_{\text{ACT}}) \tag{A-5}$$

Or

$$V_{\text{ACT dry}} = 0.237672 V_{\text{NOM dry}}\sqrt{}(\frac{459.67 + T}{p_{\text{atm}}}) \tag{A-6}$$

Also, to convert standard velocity value to actual velocity:

$$V_{\text{ACT dry}} = V_{\text{STD dry}}(\rho_{\text{STD}}/\rho_{\text{ACT}}) \tag{A-7}$$

Or

$$V_{\text{ACT dry}} = V_{\text{STD dry}}\left(\frac{T + 459.67}{17.70287 P_{\text{atm}}}\right) \tag{A-8}$$

where
$V_{\text{ACT dry}}$ is the actual velocity under dry conditions (ft/min),
$V_{\text{NOM dry}}$ is the nominal velocity under dry conditions (ft/min), and
$V_{\text{STD dry}}$ is the standard velocity under dry conditions (ft/min).

The previous equations do not consider the effects of humidity; they apply only to dry-air conditions.

In some applications, it is desirable to correct standard velocity readings to actual velocities, and it also may be necessary to consider the density effects of relative humidity. If the measurements are obtained under conditions of high altitude or a combined effect of high humidity and temperature, the readings can be greatly affected.

To correct the actual velocity of the dry air values to the actual moist air values, use the following expression:[A-2]

$$V_{\text{ACT moist}} = V_{\text{ACT dry}}\left(\frac{0.621945 + w_s}{0.621945}\right) \tag{A-9}$$

where
$V_{\text{ACT moist}}$ is the actual velocity under moist conditions (ft/min), and
w_s is the humidity ratio (lb/lb).

Note that the humidity ratio, w_s, represents the pounds of water per pound of dry air, and can be obtained from a psychrometric chart if either the dry and wet bulb temperatures or the relative humidity and dry bulb temperature are measured. A psychrometric chart can be found at the National Environmental Balancing Bureau (Gaithersburg, MD) web site, http://www.nebb.org/assets/1/7/2017_NEBB_Official_Formula___Psych_Chart_Document_V1.3-updated_5.1.17.pdf.

Examples

a. The air velocity inside a room, measured using a thermo-anemometer, is 250.00 ft/min, the barometric pressure is 30.0 in.-Hg, the temperature is 85.0 °F, and the relative humidity is 95%. The instrument does not correct for actual values. Determine the actual velocity of the dry air.

   Using eq A-8,

$$V_{\text{ACT dry}} = 250\left(\frac{85 + 459.67}{17.70287 \times 30}\right)$$

$$= 256.39 \text{ ft/min}$$

b. The air velocity inside a room measured using a Pitot tube is 253.17 ft/min, the barometric pressure is 30 in.-Hg, the temperature is 85.0 °F, and the relative humidity is 95.0%. Determine the actual velocity of the moist air.

   Using eq A-6,

$$V_{\text{ACT dry}} = 0.237672 \times 253.17\sqrt{}(\frac{459.67 + 85}{30})$$

$$= 256.39 \text{ ft/min}$$

   The value for the humidity ratio, evaluated at 85.0 °F and 95% relative humidity and obtained from a psychrometric chart, is w_s = 0.02494 lb/lb.

   Then, from eq A-9,

$$V_{\text{ACT moist}} = 256.39\left(\frac{0.621945 + 0.02494}{0.621945}\right)$$

$$= 266.67 \text{ ft/min}$$

APPENDIX: LITERATURE CITED

A-1. *Measuring Actual, Standard, and Nominal Velocity with a TSI DP-CALC Micromanometer*, Revision B; TSI Application Note TSI-115. TSI Incorporated: Shoreview, MN, 2013. http://www.tsi.com/uploadedFiles/_Site_Root/Products/Literature/Application_Notes/TI-115A.pdf (accessed 23 August 2018).

A-2. *Converting Standard Velocity to Actual Velocity*, Revision C; TSI Application Note TSI-109. TSI Incorporated: Shoreview, MN, 2013. http://www.tsi.com/uploadedFiles/_Site_Root/Products/Literature/Application_Notes/TSI-109.pdf (accessed 23 August 2018).

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